VI-3177

BRDF-Constrained Optimal Facet Subdivision Algorithm Development: Phase I Final Report

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September 1997

Final Report

CONTRACT No. DAAE07-97-C-X014

Prepared for
U. S. Army
Tank-automotive & Armaments Command
Warren, MI 48397-5000

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE September 1997	3. REPORT TYPE AND DATES COVERED Final 961105 - 970831

4. TITLE AND SUBTITLE
BRDF-Constrained Optimal Facet Subdivision Algorithm Development: Phase I Final Report

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
VI-3177

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army
Tank-automotive & Armaments Command
Warren, MI 48397-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)
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14. SUBJECT TERMS
SBIR Report TACOM Visual Analysis Tool Specular Reflectance
Bidirectional Reflectance Distribution Function Facet Subdivision

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

Abstract

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Key Words

SBIR Report
TACOM Visual Analysis Tool
Bidirectional Reflectance Distribution Function
Specular Reflectance
Facet Subdivision

CONVERSIONS TO METRIC (SI) UNITS

Conversion factors for U.S. customary units to the International System of Units (SI). Symbols of SI units are given in parentheses.

To convert from	to	Multiply by
angstrom	meter (m)	1.000 000 x E -10
atmosphere (normal)	kilopascal (kPa)	1.013 25 x E +2
bar	kilopascal (kPa)	1.000 000 x E +2
barn	meter^2 (m^2)	1.000 000 x E -28
British thermal unit (thermochemical)	joule (J)	1.054 350 x E +3
calorie (thermochemical)	joule (J)	4.184 000
calorie (thermochemical)/centimeter^2	joule/meter^2 (J/m^2)	4.184 000 x E +4
curie	becquerel (Bq)*	3.700 000 x E +10
degree (angle)	radian (rad)	1.745 329 x E -2
degree Fahrenheit	kelvin (K)	$t_K = (t_F + 459.67)/1.8$
electron volt	joule (J)	1.602 19 x E -19
erg	joule (J)	1.000 000 x E -7
erg/second	watt (W)	1.000 000 x E -7
foot	meter (m)	3.048 000 x E -1
foot-pound-force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 x E -3
inch	meter (m)	2.540 000 x E -2
jerk	joule (J)	1.000 000 x E +9
joule/kilogram (J/kg) (radiation dose absorbed)	gray (Gy)**	1.000 000
kiloton	joule (J)	4.183 x E+12
kip (1000 lbf)	newton (N)	4.448 222 x E +3
kip/inch^2 (ksi)	kilopascal (kPa)	6.894 757 x E +3
ktap	newton-second/meter^2 (N·s/m^2)	1.000 000 x E +2
micron	meter (m)	1.000 000 x E -6
mil	meter (m)	2.540 000 x E -5
mile (international)	meter (m)	1.609 344 x E +3
ounce-mass (avoirdupois)	kilogram (kg)	2.834 952 x E -2
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound-force-inch	newton-meter (N·m)	1.129 848 x E -1
pound-force/inch	newton/meter (N/m)	1.751 268 x E +2
pound-force/foot^2	kilopascal (kPa)	4.788 026 x E -2
pound-force/inch^2 (psi)	kilopascal (kPa)	6.894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 x E -1
pound-mass-foot^2 (moment of inertia)	kilogram-meter^2 (kg·m^2)	4.214 011 x E -2
pound-mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601 846 x E +1
rad (radiation dose absorbed)	gray (Gy)**	1.000 000 x E -2
roentgen	coulomb/kilogram (C/kg)	2.579 760 x E -4
shake	second (s)	1.000 000 x E -8
slug	kilogram (kg)	1.459 390 x E +1
torr (mm Hg, 0 °C)	kilopascal (kPa)	1.333 22 x E -1

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The gray (Gy) is the SI unit of absorbed radiation; 1 Gy = 1 J/kg (radiation dose absorbed)

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Section 1

Introduction

The team of Visidyne, Inc. (VI) and the Space Dynamics Laboratory (SDL) of Utah State University (USU) in a Phase I Small Business Innovation Research (SBIR) project developed and demonstrated an algorithm to improve the radiometric visualization of facetted vehicle models. The effort was monitored by the Tank-automotive and Armaments Command (TACOM) of the U.S. Army under contract DAAE07-97-C-X014.

The new algorithm addressed the problem of optimizing the calculation of specular reflection from curved surfaces. A by-product of the Phase I effort was the development of a prototype tool for visualizing facetted vehicle models, tentatively named the TACOM Visual Analysis Tool (TVAT). The primary technical features of TVAT, which set it apart from other products currently available, are the rendering of surfaces characterized by complex bi-directional reflectivity distribution functions (BRDFs) and the retention of 32 bits of precision in the rendering process, while providing an interactive viewing capability. The prototype tool produces monochrome images from direct solar reflection using a single BRDF for the entire model.

Background

TACOM is interested in the development of models to assist in the design of vehicles and in the analysis of their signatures in various regions of the electromagnetic spectrum. TACOM has already developed tools to predict the radar (XPATCH) and thermal (PRISM[1]) signatures of ground vehicles. These tools render images from facetted models produced by the Facetted Region EDitor (FRED), based on solid models from CAD/CAM design tools (see Figure 1).

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[1]Keweenaw Research Center, PRISM User's Manual, Version 1.0, Michigan Technological University, Houghton, 1988.

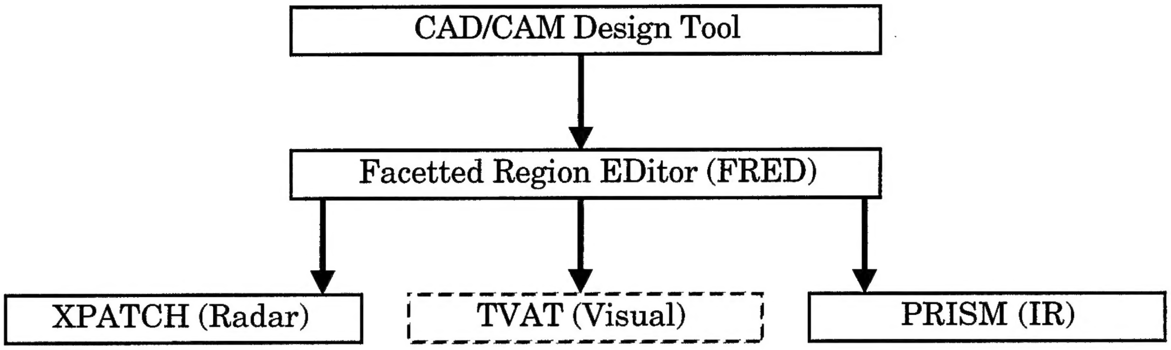

Figure 1. Relationship of solid modeling, facetization, and visualization tools.

Like XPATCH and PRISM, the Phase I prototype for TVAT starts with a facetted description of a vehicle produced by a code such as FRED from a CAD/CAM solid model description. For thermal signature modeling the facetted description must be refined depending upon the needs of the thermal modeling process[2]. Similarly, for visual modeling the facetted description must also be refined. For example, the variation in surface reflectivity associated with a camouflage pattern can be treated qualitatively with texture mapping or quantitatively by facet subdivision or rearrangement[3]. In thermal modeling the need to portray thermal contrasts accurately necessitates the subdivision of facets in the vicinity of high temperature gradients. An analogous situation exists in visual modeling. However, in this case it is the requirement to model specular reflections which necessitates the use of small facets where the surfaces are curved. In Phase I the Visidyne team addressed this need by refining the facetization of curved surfaces in accord with the narrowness and height of specular lobes in the associated BRDF. Figure 2 shows the dependence of the BRDF for AFGL-10 gloss white paint at a wavelength of 4 μm based on parameters from Sandford and Robertson[4].

[2]Jones, J., D. Gorsich, T. Gonda, and G. Bobo, "Automated Adaptive Thermal Discretization", 1995 Ground Target Modeling and Validation Conference, August 1995.

[3]Gorsich, D., J. Jones, R. Evans, and D. Thomas, "The TARDEC Visual Spectrum Analysis Model", Monterey, 1996.

[4]Sandford, B., and L. Robertson, "Infrared Reflectance Properties of Aircraft Paints", Proc. IRIS Targets, Backgrounds and Discrimination, 1985.

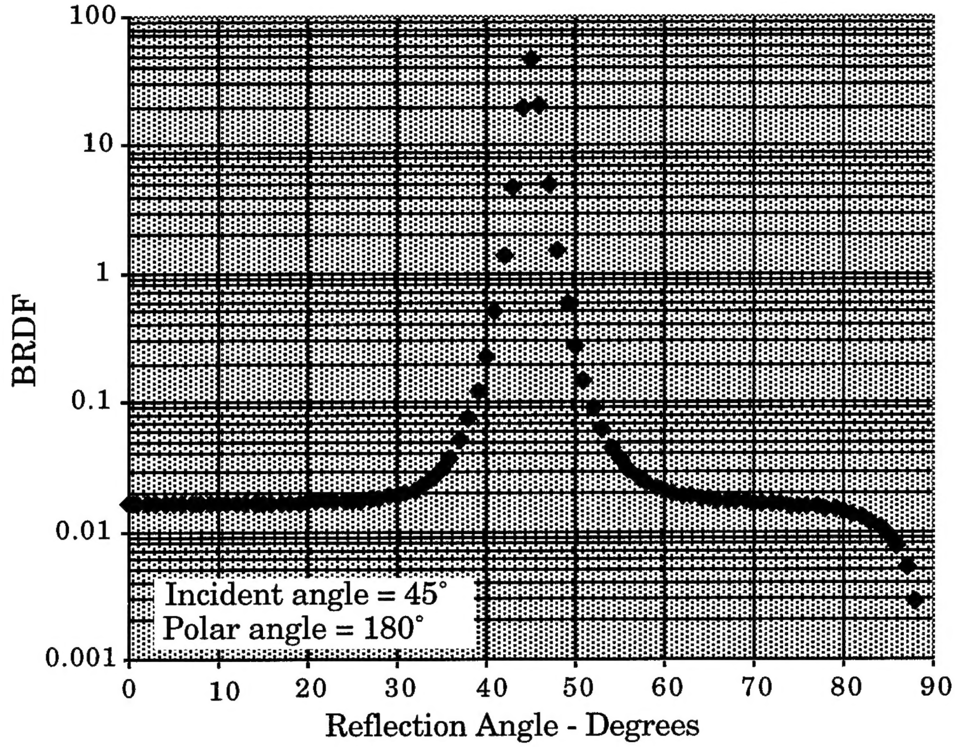

Figure 2. BRDF of AFGL-10 gloss white paint at a wavelength of 4 μm based on parameters from Sandford and Robertson.

Overview

Section 2 provides a description of the facet subdivision algorithm and Section 3 offers an example of the effectiveness of the algorithm. Section 4 describes the TVAT prototype and Section 5 indicates plans for upgrading the TVAT prototype. Section 6 offers some conclusions.

Section 2

Description of the Facet Subdivision Algorithm

In Phase I the VI team developed and coded an algorithm for subdividing facets representing curved surfaces. The goal of the algorithm was to reduce the rendering error for strongly peaked BRDFs. The team wrote a prototype TVAT to provide a framework for testing the new algorithm. The new algorithm and program were written in standard C starting with one of the examples from Angel's book[5] and take advantage of the OpenGL™[6] graphics library.

Direct Reflection of Sunlight

To appreciate the operation of the facet subdivision algorithm consider the relationship between the reflected radiance and the solar flux. The radiance L from the solar flux F_s reflected from a segment of a surface is given by:

$$L = F_s \times \rho(\theta_i,\theta_r,\phi) \times cos(\theta_i), \tag{1}$$

where ρ is the BRDF for the surface. The BRDF depends upon θ_i, the angle between the incident solar flux and the surface normal, θ_r, the angle between the reflected ray and the surface normal, and ϕ, the polar angle between the projections of the incident and reflected rays on the surface. For a Lambertian (diffuse) surface, the BRDF is a constant equal to $1/\pi$. However, for general surfaces the BRDFs can exhibit peaks as in Figure 3.

Facet Subdivision Algorithm

The maximum variation in the radiance L with finite angle α, where α is either θ_i, θ_r, or ϕ, is proportional to the product of the gradient of the BRDF function and the cosine of the incident angle:

$$\Delta L \quad F_s \times \nabla [\, \rho\, cos(\theta_i)\,] \times \Delta\alpha \,. \tag{2}$$

Equation (2) can be inverted to give the change or error in an angle α associated with a prescribed error in radiance ΔL:

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[5]Angel, E., Interactive Computer Graphics, A Top-down Approach With OpenGL, Addison-Wesley, Reading, MA, 1997.

[6]OpenGL™ Architecture Review Board, OpenGL Reference Manual: The Official Reference Document for OpenGL, Release 1, Addison-Wesley, 1992.

$$\Delta \alpha \quad L / \{ F_s \times \nabla [\rho \cos(\theta_i)] \} . \tag{3}$$

The selection of a threshold angular separation for facet normals then becomes a simple matter of searching the domain of the BRDF function (times $\cos \theta_i$) for the maximum gradient. To be specific, the user specifies a relative error parameter, ε, from which the threshold $\Delta \alpha_t$ is calculated as:

$$\Delta \alpha_t = \varepsilon / \max\{ \nabla [\rho \cos(\theta_i)] \} . \tag{4}$$

Any facet which has normals with angular separation exceeding $\Delta\alpha_t$ is subdivided. One of the major technical objectives of the Phase I effort was to validate this approach. A simple sampling and search algorithm was implemented to determine the maximum gradient $\nabla [\rho \cos(\theta_i)]$ of the product of the BRDF function and the incident flux normalization factor.

Section 3

Effectiveness of the Facet Subdivision Algorithm

Quantitative analysis of the performance of the facet subdivision algorithm can be accomplished through the use of ellipsoidal surfaces. An ancillary tool was assembled to generate facetted ellipsoids of arbitrary fidelity in FRED format. The tool was based on a program written by Jaewoo Ahn[7]. Figure 3 shows an ellipsoid with semi-major axes in the proportions 1:2:3 rendered by the TVAT prototype. The ellipsoid is represented by 73,728 facets, uses the Sandford-Robertson model for AFGL-01 camouflage paint, and was employed as a reference for evaluating the effectiveness of the facet subdivision algorithm.

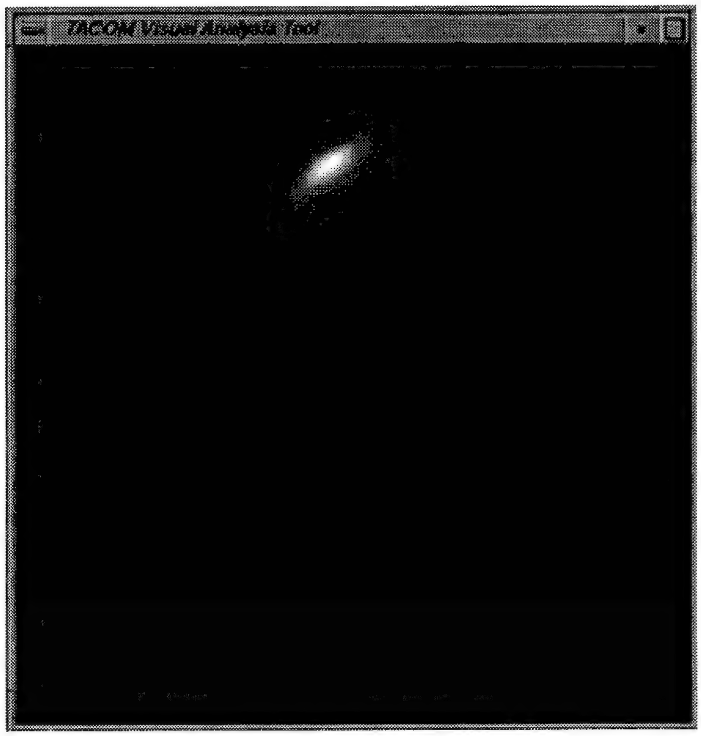

Figure 3. High-resolution ellipsoid rendered by the TVAT prototype.

Figure 4 compares the rendering of the specular reflection from a 512-facet ellipsoid as a function of the user-specified error parameter for the same geometrical situation shown in Figure 3.

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[7]Ahn, J., "Fast Generation of Ellipsoids", in <u>Graphics Gems V</u>, Alan Paeth, ed., AP Professional, Boston, 1995.

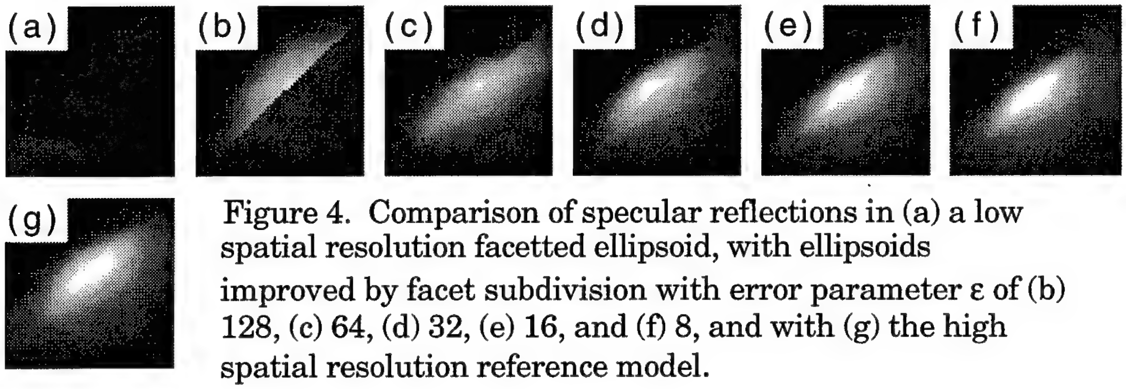

Figure 4. Comparison of specular reflections in (a) a low spatial resolution facetted ellipsoid, with ellipsoids improved by facet subdivision with error parameter ε of (b) 128, (c) 64, (d) 32, (e) 16, and (f) 8, and with (g) the high spatial resolution reference model.

Visualization of the ellipsoid using only 512 facets (Figure 4a) results in a loss of resolution of the specular reflection for many viewing angles. As large facets are subdivided into smaller ones, the specular reflection is again resolved (Figure 4b-f). Figure 5 shows the average error in the subdivided 512-facet model as a function of the error parameter.

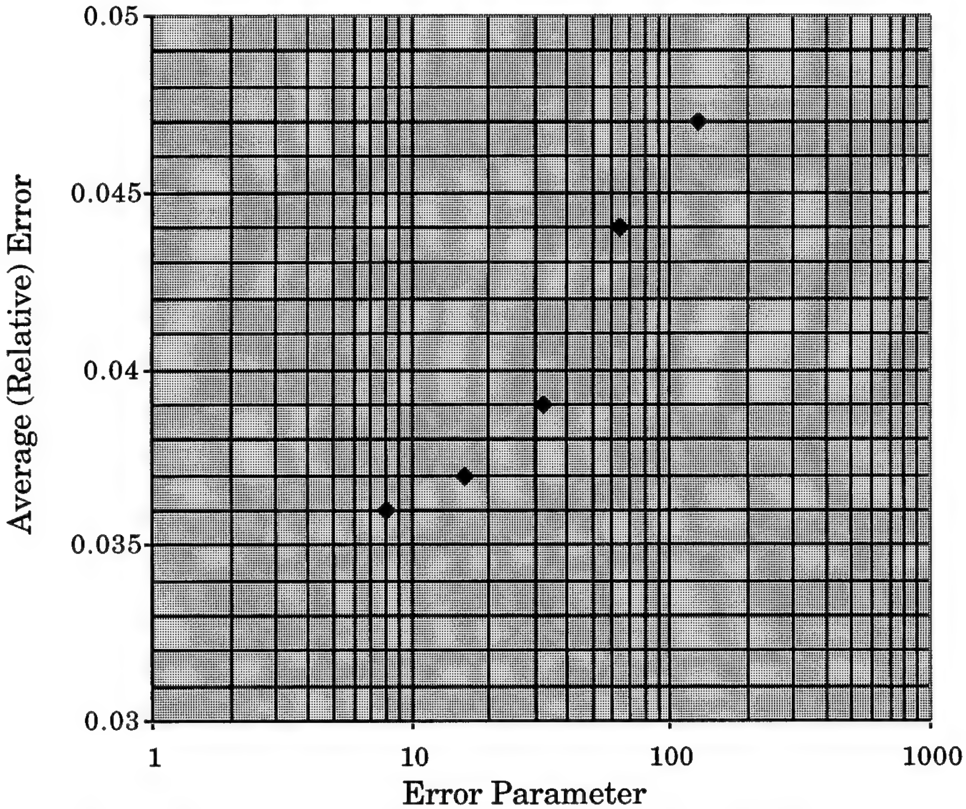

Figure 5. Average error relative to the high-resolution model of a 1-2-3 facetted ellipsoid as a function of the facet subdivision error parameter used.

The reduction in error needs to be weighed against the increase in

computational burden as manifested by the increase in the number of facets. Figure 6 shows the dependence of the number of facets on the error parameter.

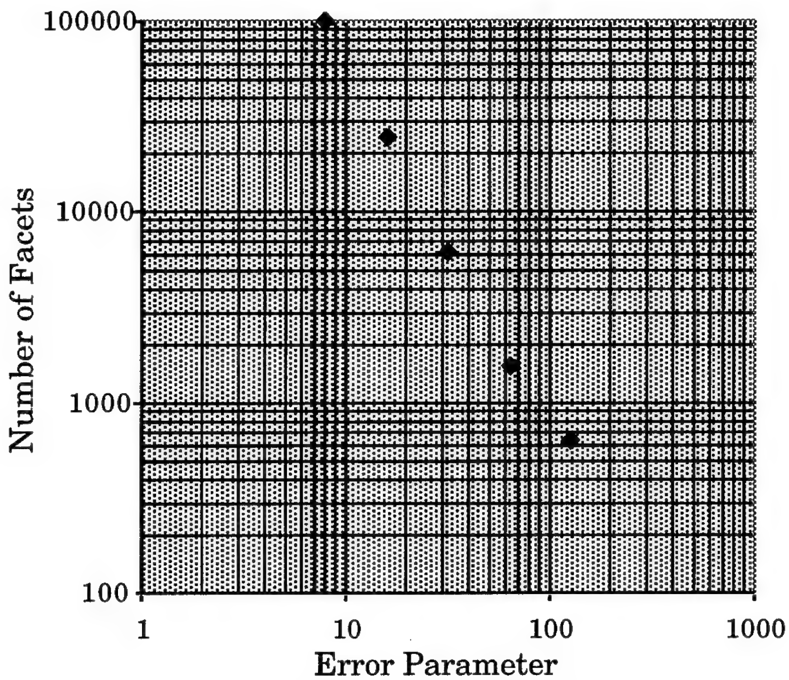

Figure 6. Dependence of the number of facets on the error parameter for subdividing the 512-facet 1-2-3 ellipsoid.

The relatively steep increase in computational burden coupled with the marginal decrease in average error with decreasing error parameter suggests that one ought to explore alternatives. Figure 4 suggests that facet subdivision is important only in the vicinity of specular points. An approach similar to the "level-of-detail" tactic[8] used to decrease the complexity of facetted models as a function of range might prove helpful. In the current situation, the facet subdivision would be applied only in the vicinity of specular points.

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[8]Williams, L., "Pyramidal Parametrics", Computer Graphics, 17(3), p 1-11, 1983.

Section 4

The TVAT Prototype

The TVAT prototype was designed to utilize vehicle models in the FRED format. Figure 7 shows a sample image of an HMMWV produced by the TVAT prototype from a facetted model database supplied by TARDEC. The specular reflection from the windshield is readily apparent in the image. Note that the gain in the image has been adjusted so that the windshield glint is not saturated; consequently the rest of the vehicle appears dark.

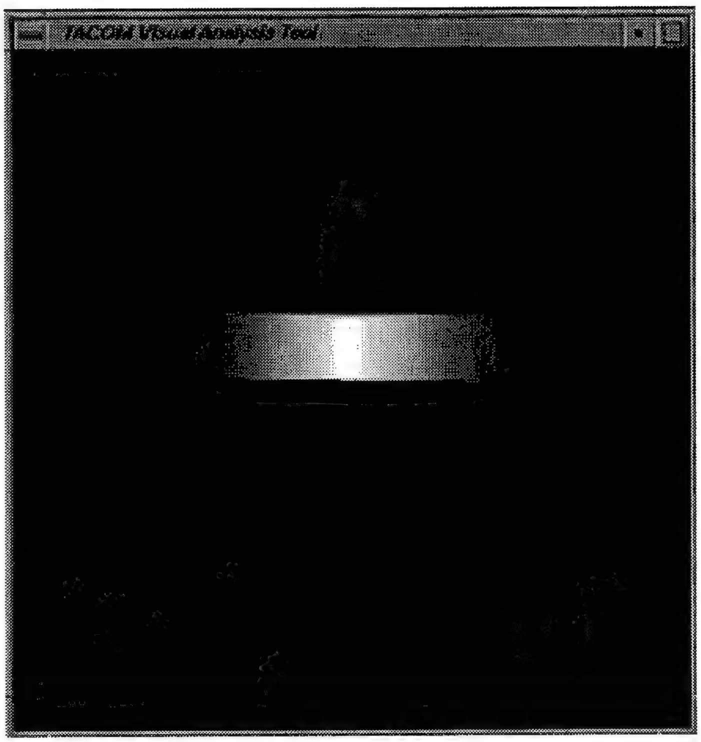

Figure 7. Screen grab of HMMWV rendered by TVAT prototype using the Sandford-Robertson model for AFGL-10 gloss white paint.

Although the TVAT prototype can be directed to grab the screen buffer, convert the pixel colors to radiances, and output the image as real (floating point) radiances in an FITS (Flexible Image Transport System) file[9], this procedure results in degraded values because of the 8-bit dynamic range used in displaying images on the screen. To avoid this limitation a module was written to render the vehicle in

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[9]Geldzahler, B., A User's Guide for the Flexible Image Transport System (FITS), Applied Research Corp. 1990.

software. Figure 8 displays the same scene shown in Figure 7, but retaining 32 bits of precision. The FITS-format output is displayed using SAOimage, a 2-dimensional scientific data visualization tool developed by the Smithsonian Astrophysical Observatory. Note that a log scale is used because of the great dynamic range associated with specular reflections.

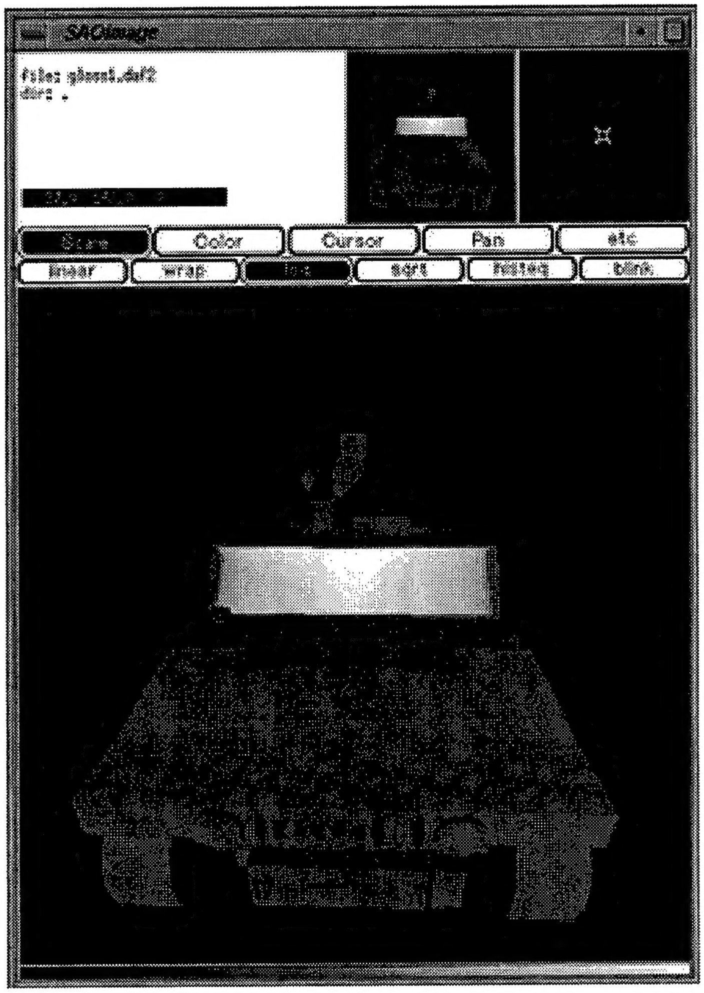

Figure 8. Image of a HMMWV retaining 32 bits of precision displayed in SAOimage using a log scale.

Section 5

Future Plans

In a Phase II effort the TVAT prototype could be developed into an operational tool for visualizing vehicles (see Figure 9). The vehicles would be represented by facetted models of their surfaces. The tool would allow designers to view vehicle configurations in visual bands. They would be able to change lighting conditions and viewing bands, and interactively adjust the viewer location. They would be able to input a digital image as a backdrop for the vehicle, output a composite image, and use it to quantify vehicle detectability.

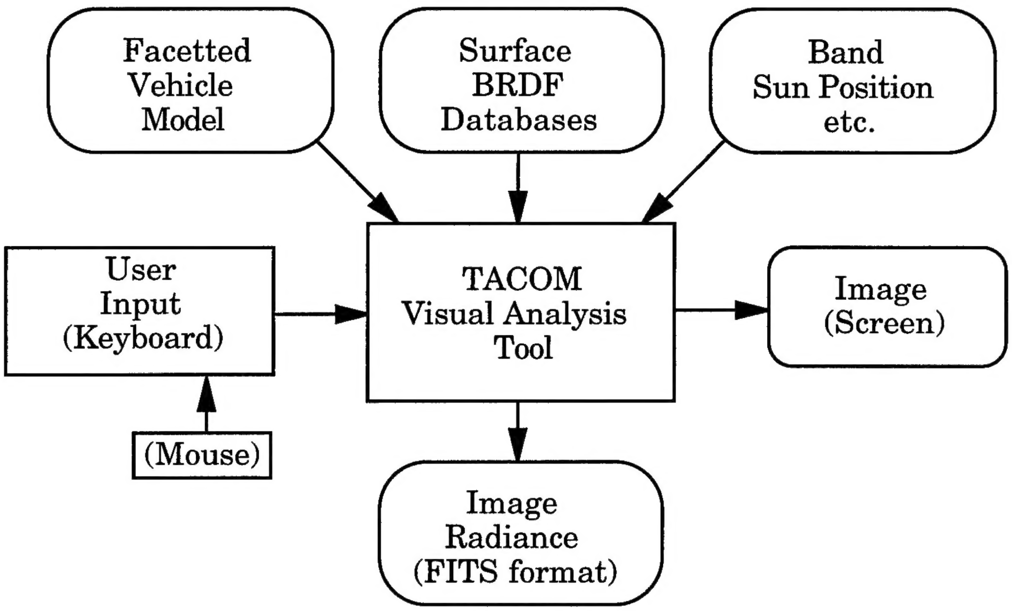

Figure 9. Diagram for an operational version of TVAT.

Table 1 lists the code improvements the VI team recommends to develop the TVAT prototype into an operational tool. The tasks and approaches are described in the VI team's Phase II proposal[10] and discussed briefly by DeVore et al.[11].

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[10] Visidyne, Inc., and Utah State University / Space Dynamics Laboratory, 1997, TACOM Visual Analysis Tool Development, VI-3086, Visidyne, Inc., Goleta, CA.

[11] DeVore, J. D. Baker, and D. Gorsich, 1997, "BRDF-Constrained Optimal Facet Subdivision Algorithm", presented at the Ground Targets, Modeling and Validation conference, Houghton, MI.

Table 1. Tasks to Develop Operational TVAT.

#	Task
1	Shadows
2	Generalized radiative transfer
3	Monochrome to 3-color conversion
4	Background from quantitative imagery
5	Polarization
6	Association of facets with BRDFs
7	Camouflage patterns
8	Model description standardization
9	Calculation speedup
10	GUI improvements
11	Verification and validation
12	Documentation

Section 6

Conclusions

Accurate visualization of specular reflections requires enhancing the facet resolution of curved surfaces. Optimal facet subdivision can mitigate this problem, but at the computational cost associated with an increased number of facets. A "level-of-detail" approach could mitigate the increased computational cost by applying the subdivision only in the vicinity of specular points.

A prototype TACOM Visual Analysis Tool was written to test the optimal facet subdivision algorithm. The new tool provides 8- and 32-bit quantitative images, but only for direct reflection of solar radiation. An operational tool can be based upon the prototype.

Acknowledgements

The author is pleased to acknowledge a number of individuals for their contributions to this project. Doran Baker (USU) was co-principal investigator for Utah State University. David Gorsich (TARDEC) monitored the project for TACOM. Scott Murdock (VI) wrote the FITS output file module. Troy Johnson (USU/SDL) developed a graphical user interface for the prototype TVAT. A.T. Stair, Jr. (VI) and Pedro Sevilla (USU/SDL) supported the program development. Steve Turcotte (USU) and Gene Ware (USU) contributed to the preliminary laboratory experimental design. Chip Tolle (USU) consulted on the project. Jack Jones (TARDEC) supplied several FRED-format model databases. Roger Evans (TARDEC) also supplied a FRED-format model database and consulted on the project.